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PROSPECTS FOR INVESTIGATING UNUSUAL NUCLEAR REACTION ENVIRONMENTS USING THE NATIONAL IGNITION FACILITY[#]

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The standard capsule design[1] and other laser plasma targets at the National Ignition Facility offer the possibility of generating and studying thermal rates for significant astrophysical fusion reactions such as $^3He(^3He,2p)\alpha$, $^7Be(p,\gamma)^8B$, and $^{15}N(p,\alpha)^{12}C$. At present the "S" factors for these reactions are determined either by extrapolation from higher energy scattering data[2,3] or by underground laboratory, low event rate experiments such as at LUNA[2,3] on un-ionized atoms with concomitantly large screening corrections. The ability to directly generate astrophysical fusion reactions in thermonuclear plasmas will be complemented by new, ab initio, "no frozen core" detailed shell model predictions for such light ion reactions.[4] In addition, the expected fluence of neutrons from the main $D + T \rightarrow \alpha + n$ burn reaction, is high enough to drive 10-20% of seeded spectator nuclei into excited states via (n,n') reactions. Furthermore, the ~2% 'minority' $D + D \rightarrow {}^3He + n$ can drive reactions pertinent to the r, s, and p process nucleosynthesis of heavy elements,[5] including branches that pass through excited states with t > 10 ps, that can be studied using particle spectroscopy and radiochemistry[6] Additionally, for the first time, it will be possible to measure the effects of plasma screening on thermonuclear reactions. In the latter arena it will be possible to address the controversy of whether or not there are significant quantum corrections to Salpeter screening.[7] Radiochemistry measurements of noble gas end species can be made with very high efficiency with only ~ 10^4 atoms required. Solid collection systems are being developed as well (with 10^{7-8} atoms required at present). Because the capsule is essentially thin to neutrons, the reaction rate on an advected set of marker nuclei is a linear functional of the neutron source distribution. Determining this source function is thus computationally analogous to similar problems in medical imaging.[8]

INTRODUCTION

The potential of the National Ignition Facility for creating and probing high energy density plasmas has been the subject of serious analysis for some time. However, while inertial fusion proper has long been a key goal of the NIF program, the general study and exploitation of nuclear reactions generated in inertial fusion capsules has just begun.[9] In fact, the unique conditions associated with ignition at NIF offer the prospect of being able to study significant, previously difficult to measure or calculate astrophysical reactions. In addition, related nuclear reactions, used to produce radiochemical diagnostic products can help determine characteristics of the burning plasma.

The unique conditions associated with burning inertial fusion capsules fall into the categories of thermonuclear fusion per se and high neutron flux and are as follows: successful runaway burn in NIF capsules produces widely differing ion and electron temperatures greatly exceeding the 1 keV equilibrium temperature at the center of the sun thus exhibiting weaker plasma screening conditions; the main $D + T$ + n burn reaction produces about 10^{19} neutrons within about 200 keV of 14 Mev in 20 ps. Because this time scale is short compared with a typical excited state nuclear gamma decay lifetime, it is appropriate to focus on the neutron fluence of about 1-2 10^{23} neutrons/cm^2 at the ablator surface. Thus, for typical neutron driven partial cross sections of about a barn (10^{-24} cm^2), 10-20% of seeded spectator nuclei will be driven into excited states capable of participating in multiple step reactions.

Because the extraction of basic nuclear physics information will be difficult, we advocate initially exploiting known or computed nuclear data for capsule diagnostic purposes. Eventually, well-characterized implosions will be applied to probe nuclear physics.

ASTROPHYSICAL APPLICATIONS OF FUSION CONDITIONS

Thermonuclear reaction rates between species i and j are of the form

$$R \sim \sigma_{ij} v_f \qquad \sigma_{ij} = \frac{S_{ij}(\varepsilon_p)}{\varepsilon_p} e^{-\pi(\varepsilon_G/\varepsilon_p)^{1/2}}$$

where E_G is the relevant "Gamow energy," E_p is the projectile energy, $S_{ij}(E)$ is the S factor and f denotes the plasma thermal average weighting function. S factors are typically extrapolated to very low event rate stellar conditions from much higher energy data importantly including assumptions about the presence or absence of Breit-Wigner resonances.[2,3] These extrapolations also include large 'cold' electron screening effects. Present ab initio calculations of key rates, such as ^{3}He(^{3}He,2p) are accurate to ~50%, motivating new experiments and calculations. Figure 1 displays S factor extrapolations for this rate, including results from the LUNA experiment.
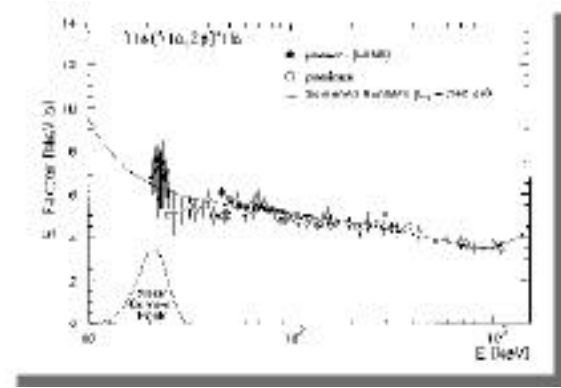

Figure 1 – Experimental S(E) variation for ^{3}He(^{3}He,2p) including cold atomic screening.[2,3] Note a possible Breit-Wigner resonance in the neighborhood of the Gamow peak for a 1 keV solar plasma.

Under solar conditions at 1 keV, the pp-I cycle, beginning with protons and ultimately producing ^{4}He via ^{3}He(^{3}He,2p)a is the main energy producing pathway. The standard solar model integral prediction[10] for the ^{8}B neutrino deficit relies on both the ^{3}He(^{3}He,2p) and ^{3}He(^{4}He,)^{7}Be rates (the pp-II and pp-III precursors) and has been verified to about 10-20% by observation of transmuted neutrino species.[11] Accurate measurements and computations[4] of these rates under near solar conditions would further the determination of neutrino masses and mixing angles as well as other astrophysical structure investigations such as helioseismology.[12]

As one of a sequence of cases proposed to explore a range of ion temperatures, a capsule with 10^{17} ^{3}He atoms (due to T decay) brought to 8 keV at 100 gr/cc produces approximately 10^8 ^{3}He(^{3}He,2p) reactions, possibly measurable through proton spectroscopy.[9]

Likewise, ^{3}He(^{4}He,)^{7}Be might be measured by a combination of gamma spectroscopy and Be radiochemistry. Finally, key CNO cycle reactions such as ^{15}N(p, a)^{12}C may be measured. In each of the cases, as has already been noted in Omega nuclear spectroscopy experiments,[9] one must devise ways to distinguish between the desired thermal rates characterized by a well-defined ion temperature, and parasitic in-flight reactions.

Finally, plasma screening, though a modest correction compared to the large screening effects already noted for E 40 keV in cold, light atoms, remains an important practical and intellectual question. Long ago, Salpeter pointed out that classical Debye screening of the Gamow barrier enhances the pp and p(^{7}Be,)^{8}B reactions by 5 and 20% respectively.[2,7]

$$_{Salpeter} = {}_0 \exp(e_1 e_2 \kappa_D \beta)$$

$$\kappa^2{}_D = 4\pi (Z_s e)^2 \beta n_{s\,\beta}$$

Here, e_1 and e_2 are the charges of the fusing ions, $_D$ is the Debye wavevector and n_s and Z_s respectively are the density and charge of the plasma species s. The question remains, of whether 'off momentum shell' effects cause significant quantum corrections to the Maxwell-Boltzmann (or Fermi-Dirac) form of the weighting function f in either the solar case or for denser, cooler stars.[7] Brown and Sawyer's equilibrium prediction goes like $_D$ $_e$ (where $_e$ is the electron thermal wavelength) and is small:

$$\sim - {}_0(\beta e_1 e_2 \kappa_D{}^2 \lambda_e)/8$$

In contrast, from non-equilibrium considerations lead to large modifications via changes in f that also depend on the ion mass through the ion-plasma collision frequency $_p$:

$$f(p) = f_{MB} + \frac{h\nu_p T}{2\pi \varepsilon_p{}^2} e^{\frac{\mu}{T}} \qquad \sigma_{ij}(\varepsilon_p) = \frac{S_{ij}}{\varepsilon_p} e^{-\pi(\varepsilon_G/\varepsilon_p)^{1/2}}$$

$$\sigma_{ij} v_f / \sigma_{ij} v_{f_{MB}}$$

In capsules, multi-temperature, non-equilibrium effects will further complicate this question.

HIGH NEUTRON FLUENCES, R P AND S PROCESS, EXCITED STATE AND DIAGNOSTIC REACTIONS

Figure 2 shows the neutron spectrum resulting from a 'borderline' DT implosion. As noted above, while the capsule is 'thin' to neutrons up to ~ 10%, these 10% corrections can drive minority, but measurable multiple step reactions. The capsule is dominated by the hard component around 14 MeV due to D + T + n that has no analog in astrophysical nucleosynthesis. However, there is also a useful, softer component ~ 2 MeV due to D + D ^{3}He + n, as well as neutron elastic scattering.
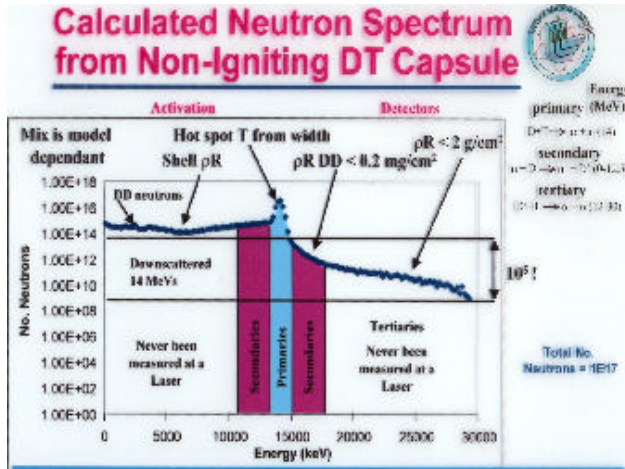
Figure 2 - Calculated neutron spectrum for a marginal ignition capsule with about 100 kilojoule yield. The chief scattering or in-flight secondary/tertiary reaction mechanism responsible for populating the spectral bin in question labels the spectrum.

Nucleosynthesis of the elements beyond iron is dominated by series of (n,) reactions driven by neutrons of E<1-2 MeV that fall into the categories of "r and s process" depending on whether the flux of neutrons is greater or less than the pertinent product beta lifetime. While the relative importance of s and r process for most isotopes is known, the issue of their astrophysical site(s) and variety of mechanisms (particularly for r process) remains open.[5] Figure 3 shows the nucleosynthesis pathways for mid-Z elements, illustrating the importance of competing paths. Unlike the low Z, charged particle, few body reactions discussed above, computing these neutron reactions requires a statistical (Hauser-Feshbach) approach.[3] For the hard neutron reactions expected at NIF, the aggregate uncertainty for the total cross section for all relevant channels such as (n,2n) at a given energy is surprisingly only about 5-10%. This is because it is controlled by unitarity and the fact that above threshold, a few reactions of the (n,xn) type dominate because of their large phase space. However, the needed information on lower energy branching ratios is less well known. Experiments with radiochemical tracers at dopant levels low enough to leave D+T ignition unperturbed would thus be important way to disentangle these networks.

It should also be remarked that these experiments taking advantage of observing reactions on the large excited state fraction of the marker nuclei (with lifetimes as short as 10 ps) are complementary to those proposed at a rare isotope accelerator intended to study reactions on much longer lived (true isomers and beta unstable ground states).[13]
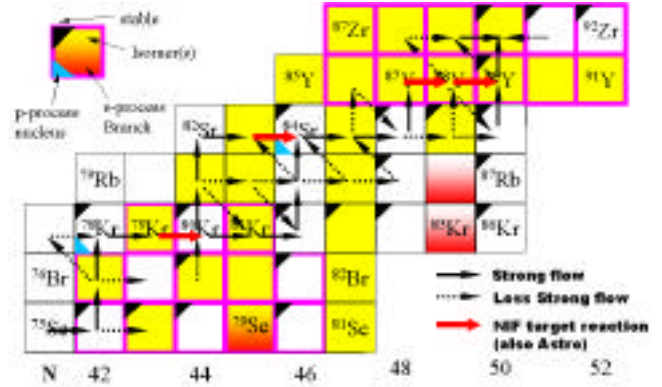

Figure 3 – Neutron driven nucleosynthesis networks for isotopes with Z ranging from 34 to 40, including r, s, p process branches, important isomeric intermediate states,[5] and possible practical NIF tracer overlaps.

Focusing on the example of Yttrium (Z=39) (n,2n) and (n,) reaction network in figure 4, one sees typical pathways controlled by the hard capsule spectrum ("anti r process").

At ^{89}Y capsule (e.g. inner ablator) dopant levels of 10^{15}, the basic 'minority' (n,) reaction, given the computed capsule flux for neutrons with E   2 MeV and   ~ 100 millibarns, produces 10^{11} ^{90}Y atoms, with various branches still measurable, though reduced proportionately.
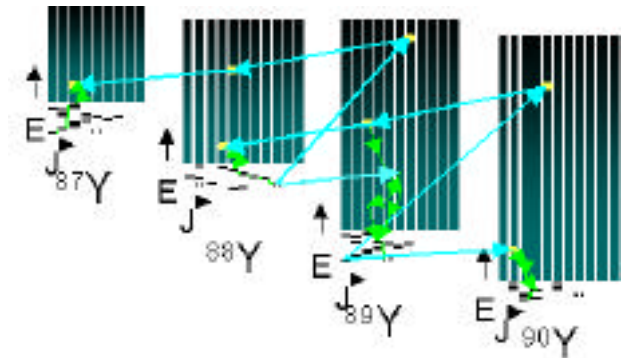

Figure 4 –Yttrium (Z=39) reaction network shows the role of low lying discrete states as well as the higher quasi-statistical continua. Both (n,2n) and (n,) are shown.

It is important to emphasize that, unlike the aforementioned charged particle case, the rates (which we have already noted to be well bounded) for the main (n,2n) neutron driven reactions are essentially a linear function of the spectator nucleus position. While disentangling the complex networks involves sifting through the minority reaction branches, the main reaction only depends on the neutron source function from the local D + T   + n distribution. Therefore, the neutron reactions on multiple advected target nuclei can give tomographic information on the

rate of capsule burn using algorithms similar to medical imaging.[8]

RADIOCHEMISTRY AND GAS SAMPLING

One may contemplate two complementary measurement schemes: product spectroscopy and radiochemistry. The former has already been successfully applied as a diagnostic at the Omega laser.[9] Here we turn to radiochemistry. For noble gas end species such as He, Ne, Ar, Kr, Xe, gas sampling from the pumping the target chamber has, in principle, nearly perfect efficiency. Figure 5 shows a schematic of the gas sampling/recovery system soon to be tested at the Omega laser. In this scheme, after recovery, the error in isotopic identification is essentially statistical. Therefore, recovery of only 10^4 atoms is required for 1% accuracy. This easily meets the requirements of most of the reactions we have considered. The situation with solid recovery is presently quite different, with the subtended solid angle of detection surfaces ($\sim 10^{-4}$) being the major handicap. For these cases, recovery of $\sim 10^8$ atoms is required to produce the same accuracy. Though adequate for some of the neutron driven reactions, this situation clearly invites innovation!
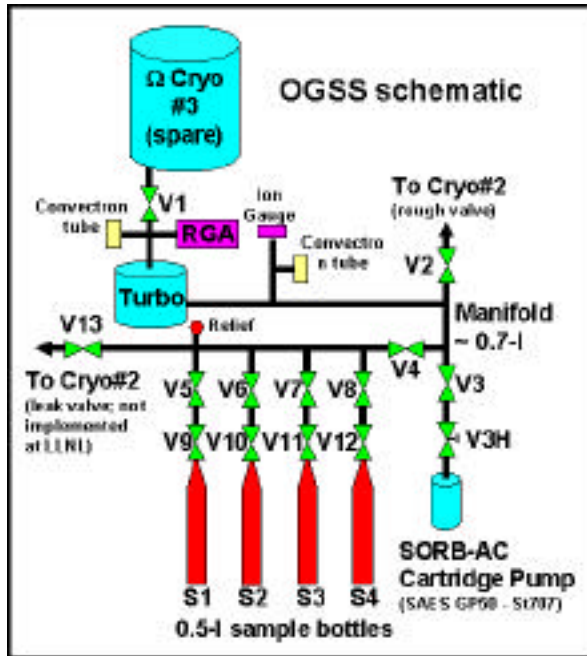

Figure 5 – Schematic of the Omega Gas Sampling System.[6]

CONCLUSIONS

In summary, we have proposed two broad classes of nuclear physics experiments at the National Ignition Facility. Both utilize ignition/implosion capsules. The first is pertinent to the standard solar model and CNO cycle stars as well as to the validation of new ab initio few body shell model calculations. These are low Z

charged particle fusion reaction experiments with the goal of pinning down their 'astrophysical' S(E) factors to high accuracy. With the specific (indirect) application to neutrino physics, to complement the LUNA experiments on $^3He(^3He,2p)$ as well as the neutrino mixing results from SNO, one desires rates with better than 10% accuracy – clearly a very tall order! For other applications, such as confirmation of CNO cycle rates, and the shell model calculations, the goal is to obtain rates with accuracies better than 50%. The absence of large 'cold' atomic screening corrections constitutes an important advantage of measuring these rates directly in thermonuclear plasmas.

The second class of experiments would utilize the enormous neutron flux to produce multiple step spectator reactions relevant to r and s process nucleosynthesis. In this case, capsule experiments would be unique, though the task, using radiochemistry, of disentangling the complex reaction networks is daunting.

These experiments are complementary to the application of spectator reactions to the analysis of capsule burn. Because their integrated rate is (up to 10% corrections) a linear functional of the local rate of burn (neutron generation), the neutron reactions are a particularly promising diagnostic.

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13. The Rare Isotope Accelerator is a proposed means to study reactions on radioactive species with lifetimes long enough for re-insertion. Thus RIA will be complementary to nuclear physics regimes probed at the National Ignition Facility. See the ANL RIA website and the references therein at http://www.phy.anl.gov/ria